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# Continuous harvesting costs in sole-owner fisheries with increasing marginal returns

**by**

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**Abstract**

We develop a bioeconomic model to analyze a sole-owner fishery with fixed costs as well as a continuous cost function for the generalized Cobb-Douglas production function with increasing marginal returns to effort level. On the basis of data from the North Sea herring fishery, we analyze the consequences of the combined effects of increasing marginal returns and fixed costs. We find that regardless of the magnitude of the fixed costs, cyclical policies can be optimal instead of the optimal steady state equilibrium advocated in much of the existing literature. We also show that the risk of stock collapse increases significantly with increasing fixed costs as this implies higher period cycles which is a quite counterintuitive result as higher costs usually are considered to have a conservative effect on resources.

Keywords: Bioeconomic modelling; Stock collapse; Fixed costs; Pulse fishing; Cyclical dynamics; Increasing marginal returns.

# 1 Introduction

Most of the literature on fisheries economics assumes that the revenue function is concave in harvest (decreasing marginal returns), and in most cases, especially in the sole owner case, the solution converges to an optimal steady state equilibrium. After such an equilibrium has been established, harvest and stock levels remain constant forever. There are, however, various reasons why increasing marginal returns (non-concavities) may be relevant in fisheries models, and especially in the case of sole owner fisheries or cooperative games. Such reasons may for example be sharing of information, co-operation between vessels on the fishing grounds, economies of scale in the technology, etc. It is, however, not likely that these phenomena will occur in competitive fisheries or non-cooperative game situations as the agents there will have no incentives to co-operate, share information or apply economies of scale beyond their own individual benefit. In the presence of non-concavities in the revenue function the optimal solution may no longer be a steady state equilibrium. Optimal solutions may consist of various types of cyclical policies or pulse fishing implying, among other things, increased danger of stock collapse even in the sole owner or cooperative case.

Empirically increasing returns have been found to exist for species such as North-Atlantic cod (Hannesson [6]) and North Sea herring (Bjørndal and Conrad [1]). Hannesson [6] found pulse fishing to be optimal for the cod using an age-structured model.

The dynamic optimization problem unquestionably becomes harder to solve in the increasing return case as standard assumptions about dynamic optimization theory fail. Also numerical solutions become more difficult to obtain as no rate of convergence can be derived from standard theory. In order to solve the problem we have used a discretization algorithm described in Maroto and Moran [16] in order to estimate the value function and the corresponding optimal policy numerically.

In the present paper a bioeconomic model is applied to analyze a sole-owner fishery with increasing returns to effort level using a stock dependent harvest function. The sole-owner case may also represent a cooperative case through a construction like a Regional Fishery Management Organization (RFMO). Special emphasis is put on the combined effects of increasing returns and fixed costs. Fixed costs are here defined as avoidable fixed costs (AFC); that is costs that are fixed in the sense that they are independent of the volume of the harvest as long as harvest is positive, but they become zero when harvesting ceases. In practice, these can be thought of as the sum of actual harvest-independent costs such as e.g. minimum wages to the crew, etc., and the opportunity cost of harvesting; that is the revenue from the best alternative activity. Re-entry costs are not considered as it is supposed that the vessels use more or less the same gear and equipment when they engage in other fisheries. Hence entry and exit to and from particular fisheries are considered costless.

The model consists of a continuous harvest function within each period in order to take into account the change in the fish stock that takes place during the fishing season. Hence the cost of fishing is also a continuous function within the season. After harvesting has taken place there is a discrete updating of the stock between the periods.

The main contribution of the present paper compared to the existing literature is to show the following: First, in the presence of increasing marginal returns to effort level in a stock dependent harvest function the optimal steady state equilibrium advocated in much of the existing literature can be suboptimal. When there are increasing returns, cyclical policies can be optimal regardless of the magnitude of the AFC. Further, in contrast to the standard literature (Reed [20]; Lewis and Schmalensee [13]), such cyclical policies are optimal even without introducing re-entry costs. In the North Sea herring case considered in our numerical example such re-entry costs are not relevant as the vessels have several alternative fisheries to choose among. Although the cyclical policies take the form of "trigger recruitment - target escapement" policies, it is important to note that in our case these are caused by the trade-off between discounting the future and the convexity of the revenue function in addition to possible fixed costs. In traditional models with concave revenue such policies will never occur without some sort of fixed costs or re-entry costs.

Secondly, we show that if the harvest function depends on the stock in the beginning of each period, then a high, but still reasonable, discount rate can cause extinction to be optimal even for stocks with high growth rates and in the absence of fixed costs. In the case of lower discount rates (higher discount factor values), the resource might be in danger of collapse because cyclical optimal policies drive the resource below the precautionary approach reference point proposed by the International Council for the Exploration of the Sea (ICES). This can be regarded as extensions of results obtained in Maroto and Moran [17] where we, in contrast, use a stock dependent harvest function. Previously, a proper form for the harvest or cost function that takes account of the change in the stock during the fishing season has not been established except for the trivial case of the Schaefer production function (e.g. Jaquette [10], Reed [20]), and for the case in which the production function is non-linear in stock level (Reed [21]) as far as we know. In this paper we formulate the cost function for the generalized Cobb-Douglas production function of which the above cases are a special case. This results in an explicit cost function that depends continuously on both stock and harvest. In this case (continuous harvesting case), we show that optimal cyclical policies can periodically drive the resource to levels approaching Safe Minimum Standards and below (stock-collapse) even in the absence of fixed costs. A continuous cost function in both harvest and stock is the appropriate cost function to use when the harvested fraction of the stock within a season is significant or when the stock is small. This implies that the stock can be economically protected as the cost of harvesting escalates when the stock comes close to extinction.

Thirdly, we show that higher AFC implies higher period cycles and consequently higher danger of collapse due to the combined effect of increasing marginal returns and AFC. This is a somewhat counterintuitive result as higher costs usually are considered to have a conservative effect on the stock.

The structure of the paper is as follows. In Section 2 we provide a background of continuous harvesting models with cyclical optimal paths. Section 3 presents the main bioeconomic model with a discussion about the continuous harvest function applied and in section 4 a discussion about the consequences of fixed costs is given. Finally, in section 5 we present some concluding remarks.

## 2 Background

Similar models as described above have been analyzed by e.g. Lewis and Schmalensee [11, 12, 13] and Reed [20]). In Lewis and Schmalensee [12] a continuous time model is used to show that under AFC and strict concavity of the revenue function either continuous harvesting or extinction represent the optimal policies. An important assumption in that paper, however, is that re-entry into the fishery after harvesting has once ceased is impossible. Lewis and Schmalensee [11], on the other hand, assume that re-entry is possible and costless. They also consider AFC, and they show that the possibility to enter and exit the fishery without re-entry costs effectively eliminates the non-convexity induced by the AFC. Further, they show that it may be optimal to maintain the stock at a constant level through so-called chattering controls (infinitely rapid changes in effort and harvest). Such policies are cyclical but the cycle intervals are of length zero and therefore infeasible for all practical purposes.

In Reed [20] a discrete time model is used to show that under positive re-entry costs an optimal policy is of the target-escapement type in the absence of AFC. A necessary and sufficient condition for the optimality of cyclical policies is given in Lemma 1 of Lewis and Schmalensee [13]. They show that optimal policies are cyclical if and only if it is optimal to change the fishery's operating status (operating/vacated) infinitely often. They get this result by taking both AFC and re-entry costs into account simultaneously. Liski et al. [14] improve the realism in their model by introducing flow adjustment costs. These adjustment costs represent flow costs associated with, for example, hiring more labour or buying new vessels. By doing this they show that for relatively high adjustment costs the usual steady state is optimal whereas for relatively low adjustment costs cyclical harvest policies become optimal.

The existence of cyclical optimal paths in present value optimization of resource management was rigorously proved by Dawid and Kopel [4] from a theoretical point of view, in a model with increasing returns to effort level in a stock independent harvest function and a piecewise linear growth function. Further research by these authors (Dawid and Kopel [5]) proved that, if the elasticity of the convex revenue function is high enough and the growth function is smooth and concave, there cannot exists an optimal steady-state path. In that paper, they showed through a numerical experiment that a concave growth function and a concave cost function might give rise to cyclical optimal paths.

The standard assumption on the growth function in the numerical analysis of Dawid and Kopel [5] left open the possibility that optimal cycles due to increasing marginal returns do exist in actual fisheries. The numerical analysis based on the data of the North Sea herring fishery described in Maroto and Moran [17] fully confirms the plausibility of existence of optimal cyclical paths in actual renewable resources management.

# 3 Bioeconomic model

In this section a bioeconomic model is developed to analyze a fishery with increasing marginal returns as well as fixed costs. There is discrete updating of the stock between the harvesting seasons and continuous harvest within the season. Thus the cost function is a continuous function of both stock and harvest during the harvest season.

The discrete population dynamics for the resource is given by

$$x_{t+1} - x_t = F(x_t) - H_t, \tag{1}$$

where $x_t$ is the total biomass at the beginning of period $t$, $F(x_t)$ is the natural surplus growth of the biomass at period $t$, and $H_t$ is the total harvest at period $t$. By defining

$$f(x_t) \equiv x_t + F(x_t) \tag{2}$$

as the recruitment (the stock at the beginning of the period) equation (1) can be rewritten $f(x_t) - x_{t+1} = H_t$. This implies a constraint on the escapement (stock after harvesting) which we call $y$. This constraint in the optimization problem described below is given by

$$y \leq f(x), \tag{3}$$

which implies $H = f(x) - y \geq 0$.

### 3.1 Costs with continuous harvesting

In this section we develop a novel cost function which is depending on the running stock size and harvest within each season. Let $h$ and $e$ be the harvest and effort rates and let $x$ be the stock at time $t$. Further, let the instantaneous production (harvest) function be a generalized Cobb-Douglas function

$$h = qe^{\alpha}x^{\beta}, \tag{4}$$

where $q$ is constant, $\alpha$ is the effort elasticity and $\beta$ is the stock output elasticity.

Total costs during the harvest season are given by

$$C = \int_0^T cedt, \tag{5}$$

where $T$ is the length of a harvest season and $c$ is the instantaneous cost per unit fishing effort. During the harvest season we assume that the stock is only being changed by fishing mortality. Hence $\mathring{x} = -h$ and

$$\begin{aligned} e &= q^{-1/\alpha} x^{-\beta/\alpha} h^{\frac{1}{\alpha}} = q^{-1/\alpha} x^{-\beta/\alpha} h^{\frac{1}{\alpha}-1} h = \\ &= q^{-1/\alpha} x^{-\beta/\alpha} h^{\frac{1}{\alpha}-1}(-\mathring{x}) = -kx^{-\beta/\alpha} h^{\frac{1}{\alpha}-1} \mathring{x}, \end{aligned} \tag{6}$$

where $k = q^{-\frac{1}{\alpha}}$. Assuming a constant harvest rate through the season, and using (6), the costs during the harvest season are given by

$$\begin{aligned} C &= \int_0^T cedt = \int_0^T -ckx^{-\frac{\beta}{\alpha}} h^{\frac{1}{\alpha}-1} \mathring{x} dt = \\ &= \int_{f(x)}^y -ckx^{-\frac{\beta}{\alpha}} h^{\frac{1}{\alpha}-1} dx = ckh^{\frac{1}{\alpha}-1} \int_y^{f(x)} x^{-\frac{\beta}{\alpha}} dx = \\ &= ckh^{\frac{1}{\alpha}-1} [x^{1-\frac{\beta}{\alpha}} / (1-\beta/\alpha)]_y^{f(x)} = \frac{ckh^{\frac{1}{\alpha}-1}}{1-\beta/\alpha} [f(x)^{1-\frac{\beta}{\alpha}} - y^{1-\frac{\beta}{\alpha}}]. \end{aligned} \tag{7}$$

The constant harvest rate in the season can be replaced by $\frac{f(x)-y}{T}$ in (7). The costs during the harvest season are then given by

$$C(x,y) = \eta \frac{f(x)^\theta - y^\theta}{[h]^\varphi} = \eta \frac{f(x)^\theta - y^\theta}{[f(x)-y]^\varphi}, \tag{8}$$

where $\eta = \frac{ckT^{\varphi}}{\theta}$, $f(x)$ is as defined in (2), $y$ is as defined in (3), $k = q^{-1/\alpha}$, $\theta = 1 - \beta/\alpha$ and $\varphi = 1 - 1/\alpha$.

The net revenue function from the fishery is given by

$$R(x, y) = pH_t - C = p\left[f(x) - y\right] - C(x, y), \tag{9}$$

where $p$ is the unit price of harvest.

In order to take into account the presence of increasing marginal returns and the relatively weak dependence between stock and catch per unit effort in this fishery, we assume an effort elasticity $\alpha > 1$ and a stock output elasticity $\beta < 1$ in (4), respectively. As described below, these parameter values are empirically estimated for fisheries on schooling stocks such as North Sea herring (Bjørndal and Conrad [1], Hannesson [7]). Notice that the harvest function estimated by Bjørndal and Conrad [1]

$$H(E_t, X_t) = qE_t^{\alpha}X_t^{\beta}, \tag{10}$$

represents the total catch during period $t$, but it is assumed here that they represent a fairly good approximation to the parameters in (8).

## 3.2 The objective functional

The objective functional is the present value ($PV$) of net revenues from the fishery

$$PV = \sum_{t=0}^{\infty} \delta^t R(x, y) \tag{11}$$

where $R$ is as defined in (9) and $\delta \in (0, 1)$ is a discount factor.

The objective function can be rewritten

$$\begin{aligned} \max_{\{x_{t+1}\}_{t=0}^{\infty}} & \sum_{t=0}^{\infty} \delta^t R(x_t, x_{t+1}) \qquad (12) \\ 0 &\leq x_{t+1} \leq f(x_t), t = 0, 1, ..., \\ x_0 &> 0 \text{ given, } R(x_t, x_{t+1}) \geq 0, t = 0, 1, ..., \end{aligned}$$

where $x_0$ is the initial stock level. If $f(x_t)$ is as defined in (2) then $f(x_t) - x_{t+1} = H_t$ in (12).

Using the dynamic programming approach, we can define the following Bellman equation associated with (12)

$$V(x) = \max_{0 \leq y \leq f(x)} \{R(x, y) + \delta V(y)\}. \tag{13}$$

Unfortunately, a closed form solution of (13) is unattainable. The required concavity assumptions on which the standard theory rests are not borne out in this situation (see Stokey, Lucas and Prescott [22]) due to the presence of increasing marginal returns. The standard theory is not able to assess any rate of convergence for the numerical algorithms. Subsequent increases in the discretization grid used in numerical computations can cause significant changes in the outputs.

We use here the approach described in Maroto and Moran [15, 16], where an alternative framework, based on Lipschitz continuity assumptions is proposed. In Maroto and Moran [16], a discretization algorithm is described for the numerical estimation of the value function and the optimal policy correspondence solutions of (13).

### 3.3 Avoidable fixed costs

Fixed costs are here defined as avoidable fixed costs (AFC); that is, costs that are fixed in the sense that they are independent of the volume of the harvest as long as harvest is positive, but they become zero when harvesting ceases. In practice, these can be thought of as actual costs that are independent of the harvest volume such as minimum wages, etc., plus the opportunity cost of engaging in the fishery. The latter is defined as the revenue from the best alternative activity. In the current model, AFC are given by

$$AFC = c^* v, \tag{14}$$

where $c^*$ is a percentage of the variable cost per vessel $c$ and $v$ is the fleet size in number of vessels which is given.

AFC as defined in (14) can be thought of as a measure of alternative activities from the fishery which range from zero to something around the annual gain rate from the present fishery.

The Bellman equation is now written

$$V(x) = \max_{\substack{0 \leq y \leq f(x) \\ R^{AFC} \geq 0}} \{R^{AFC}(x,y) + \delta V(y)\}, \tag{15}$$

where $R^{AFC}(x,y) = R(x,y) - AFC$.

Notice in Problem (15) that in the case in which $y < f(x)$, the fishery is operating ($h > 0$) which in turn implies positive $AFC > 0$. In this case, negative profits are possible. However, in the case in which $y = f(x)$, the fishery is vacated ($h = 0$) which in turn implies $AFC = 0$ in (15). In this case, $R^{AFC} = 0$. This means that the fishery may thus yield negative profits at sufficiently low levels of harvesting, even though zero harvesting would produce zero net benefits.

## 3.4 North Sea herring fishery

In order to make realistic the numerical experiments while keeping their scope of application wide enough, we take as our starting point the North Sea herring fishery.

North Sea herring is a representative case of a schooling species. In spite of its resilience and ecological value, this species has been driven to collapse by heavy economic exploitation. Indeed, the North Sea herring stock was in danger of extinction in 1977 when a moratorium on fishing had to be imposed due to the overexploitation suffered in the 1970s under an open access regime (Bjørndal [2]). In the mid-1990s the North Sea herring stock was in danger of collapse again (ICES [9]). Moreover, the medium term simulations of the ICES indicate a high probability for the stock to be below safe biological limits in future years (ICES [9]).

North Sea herring is a joint stock shared by Norway and the European Union (EU). Currently, the total quota for the fishery is allocated between the two parties with 29% to Norway and 71% to the European Union. In Bjørndal and Lindroos [3], in a setting of discrete-time game-theoretic model, it is analyzed how the total quota for this species should be shared between these two parties so that both parties are satisfied in a steady state equilibrium. Taking into account the different settings of the problems, the main contribution of our results is to formulate a continuous cost function for the generalized Cobb-Douglas production function with increasing marginal returns, which is the key step to the obtention of cyclical policies. In this article we look upon the herring fishery as if it was managed by an RFMO adopting the behavior of a sole-owner.

The standard natural surplus growth for the North Sea herring is given by the logistic function $F(x_t) = rx_t(1 - x_t/K)$ where $r$ is the intrinsic growth rate and $K$ is the carrying capacity of the environment.

In order to solve Problems (13) and (15), we use the following parameters: $p = 1,318$ NOK (Norwegian Kroner) per tonne of herring (source: Norwegian Directorate of Fisheries [18]); $c = 1,091,700$ NOK (source: Norwegian Directorate of Fisheries [18]); $v = 1000$ vessels; $r = 0.53$; $K = 5.27$ million tonnes; $x_0 = 3.591$ million tonnes (source: ICES [8]); $q = 0.06152$; $\alpha = 1.356$; $\beta = 0.562$; where $p$ is the price in the year 2000 and $c$ is the cost of operating a Norwegian purse seine for one season in the same year. We use the upper level of the fleet size of this species as a measure of the fleet size $v$. The intrinsic growth rate $r$ and the carrying capacity of the environment $K$ are based on biological data for the period $1981 - 2001$ (Nøstbakken and Bjørndal [19]). The initial value of the stock $x_0$ is from the year 2001. Bjørndal and Conrad [1] estimated the constant $q$; the effort elasticity $\alpha$ and the stock output elasticity $\beta$ (see Nøstbakken and Bjørndal [19] for details on parameter estimation).

# 4 Numerical results

In this section we apply the numerical algorithm to analyze the optimal policy dynamics in the continuous harvesting model (CH) described above. Moreover, in order to analyze the role of harvesting costs depending on the stock size at a particular time (e.g. start of the season), we also analyze the optimal policy dynamics in the case of a harvest function which depends on the stock in the beginning of each period. In this case, which we call standard harvesting case (SH), and using the harvest function (10), the harvesting costs are then given by

$$C(X_t, H_t) = cE_t = c\left(\frac{H_t}{qX_t^{\beta}}\right)^{\frac{1}{\alpha}}. \tag{16}$$

Notice that these harvesting costs (see Nostbakken and Bjørndal, 2003) depend on the stock in the beginning of each period, in contrast with the continuous harvesting costs given by the equation (8) that take account of the change in the stock during the fishing season.

All data in the example below were generated using a Compaq AlphaServer GS160 6/731 ALPHAWILDFIRE Computer, coded in standard FORTRAN 77. The stock levels in all numerical proofs have been normalized, taking the carrying capacity $K = 5.27$ (million tonnes) as unity.

## 4.1 Optimal policy dynamics without fixed costs

Results in Table 1 summarize relevant information on the optimal policy dynamics without fixed costs of both standard harvesting case (SH) and continuous harvesting case (CH). In all cases, we can observe in Table 1, columns III and VII, that cyclical policies are optimal due to the presence of increasing marginal returns. As explained in Figure 1 below, the cyclical optimal policies consist of a period of heavy harvesting followed by periods of null harvest (moratoria) until the period of harvesting is achieved again.

Results in Table 1, columns II, III, IV and V correspond to the solution of Problem (13) with cost function (16) for different discount factor values

$\delta$. This is the standard harvesting case (SH) without fixed costs.

In this case, biological extinction of the resource occurs for discount factors $\delta \leq 0.71$ (discount rates $\geq 40\%$). The lowest stock of the cycle $x_{\min}^{SH}$ is less than the minimum spawning stock biomass benchmark $B_{\lim} = 0.15$ (800000 tonnes), proposed by ICES, for discount factor $\delta \in [0.72, 0.83]$ (discount rates range from 20% to 38%). The stock is outside safe biological limits for high discount factor values $\delta \in [0.84, 0.92]$ (discount rates range from 8.7% to 19%) with $B_{\lim} < x_{\min}^{SH} \leq B_{pa}$, where $B_{pa} = 0.25$ (1.3 million tonnes) is the precautionary approach reference point proposed by ICES.[1]

Thus, our numerical experiments show that if the harvest function depends on the stock in the beginning of each period, then a high, but still reasonable, discount rate can cause stock-collapse to be optimal even for stocks with high growth rates and in the absence of fixed costs. Even in the case of discount factors higher than 0.93 (discount rates $\leq 7.5\%$), fairly above those currently applied by economic agents, the lowest stock of the cycle $x_{\min}^{SH}$ is close to $B_{pa}$ (see Table 1, column II).

Results in Table 1, columns VI, VII, VIII and IX correspond to the solution of Problem (13) with cost function (8) for different discount factor values. This is the continuous harvesting case (CH) without fixed costs.

[1] The data used to estimate the growth function are on total biomass – not on spawning stock biomass (SSB). The SSB is (according to ICES) much smaller than total biomass. The proportion of the SSB compared to total biomass has varied widely from less than 10% to more than 80%. In our comparison of biomass from our model and the minimum spawning stock biomass benchmark $B_{\lim}$ (given by ICES), the low $x_{\min}$ value is therefore even more dramatic. Therefore, it reinforces our argument because if the total biomass is below safe biological limits then certainly the spawning stock biomass must be.

With regard to the standard harvesting case analyzed above, an explicit cost function that depends continuously on both stock and harvest preserves the resource at higher stock levels. In particular, the lowest stock of the cycle $x_{\min}^{CH} \leq B_{\lim} = 0.15$ for discount factors $\delta \leq 0.75$ (discount rates $\geq 33\%$). The stock is outside safe biological limits for discount factor values $\delta \in [0.76, 0.84]$ (discount rates range from 19% to 31%) with $B_{\lim} < x_{\min}^{CH} \leq B_{pa}$. However, the stock remains inside safe biological levels ($x_{\min}^{CH} > B_{pa}$) for discount factors $\delta > 0.84$ (discount rates $< 19\%$).

Results in Table 1, columns IV and VIII correspond to the optimal harvest in the cycle for both the standard harvesting case ($H^{SH}$) and continuous harvesting case ($H^{CH}$). In all cases, we can observe that the optimal harvest in the standard harvesting case is greater than that obtained in the case of continuous harvesting and consequently the stock becomes in danger due to lower minimum stock in the cycles $x_{\min}^{SH} < x_{\min}^{CH}$. Therefore, due to the stock dependence in the costs a standard harvesting model that uses too large stock (the recruitment stock) will underestimate the total costs and thereby overestimate the value of the fishing activity. On the other hand, further numerical experiments show that, if one uses too small stock (the escapement stock) one tends to overestimate the costs and hence underestimate the value of the fishery. Under/overestimating these "unit-costs" has the normal effect of increasing/decreasing the pressure on the stock (as seen by minimum stock in the cycles $x_{\min}^{SH}$), i.e. these kind of variable costs has a conservational implication (higher cost induces more conservative harvest policy). However, in the case of continuous harvesting (CH), the optimal policy is achieved through a more regular harvesting plan that reduces the periods of null harvest, increasing the regularity of harvesting by reducing the period of the optimal cycle and preserving the stock by augmenting the minimum stock in the cycles $x_{\min}^{CH}$.

## 4.2 Optimal policy dynamics with avoidable fixed costs

Results in Table 2 summarize relevant information on the optimal policy dynamics in different settings for a discount factor $\delta = 0.9$ and different values of the AFC as defined in (14). In particular, columns III, IV,V and VI correspond to the solution of Problem (15) with cost function (16). This is the standard harvesting case (SH) with AFC. Columns VII, VIII, IX and X correspond to the solution of Problem (15) with cost function (8). This is the continuous harvesting case (CH) with AFC.

In both cases, the presence of AFC changes the optimal policy dynamics significantly. In particular, if we compare these results with that obtained in the absent of AFC, we can see that the risk of collapse of the species increases significantly even for low AFC values. For instance, in the case of $c^* = 0.1$ ($AFC = 0.109$ thousand million NOK), $x_{\min}^{SH}$ ranges from 0.25 to $0.2 < B_{pa}$, and $x_{\min}^{CH}$ ranges from 0.32 to $0.25 = B_{pa}$ (see Table 1, columns II and VI, for $\delta = 0.9$, and see Table 2, columns III and VII, for $c^* = 0.1$).

We can observe in Table 2, columns II,III, IV,VII and VIII, that higher AFC imply higher period cycles with lower minimum stocks $x_{\min}$, and consequently the resource becomes in danger ($x_{\min}^{SH} \simeq B_{\lim}$ and $x_{\min}^{CH} < B_{pa}$) due to the combined effect of increasing marginal returns and AFC. This is a somewhat counterintuitive result as higher costs usually are considered to have a conservative effect on the stock. However, in the presence of increasing marginal returns cyclical optimal policies, with periods of heavy harvesting followed by long moratoria, drive the resource below $B_{pa}$ even in the absence of AFC. Thus, if high enough AFC are also considered, then the period of the cycles increases (larger harvesting followed by longer moratoria) in order to avoid the AFC and consequently the risk of collapse of the species increases significantly.

Figure 1 represents the optimal policy dynamics with its corresponding optimal harvest $H^*$ and net revenue $R_t$ for the continuous harvesting case with $AFC = 0.218$ thousand million NOK (see Table 2, columns VII, VIII and IX for $c^* = 0.2$). In particular, Figure 1a represents the concave growth function of the resource $f(x_t)$ as defined in (2) (diagram above 45 degree line), the optimal policy correspondence (thick line), and the optimal policy dynamics from the initial stock level $x_0 = 3.591/5.27 = 0.68$ (discontinuous line). We can see in this figure that the optimal policy correspondence represents the optimal stock level in the next period $x_{t+1}^*$ (after harvesting) as a function of the current stock level $x_t$. For example, the optimal stock level $x_{t+1}^* = x_1^*$ is obtained from the initial stock level $x_t = x_0$ through the path $x_0 \to a \to b \to x_1^*$. In this way, the optimal policy dynamics from the initial stock level $x_t = x_0$ is obtained through the optimal path $x_0 \rightarrow b \rightarrow c \rightarrow d \rightarrow e \rightarrow b$ with the associated optimal stock levels $x_1^* \rightarrow x_2^* \rightarrow x_3^* \rightarrow x_4^* \rightarrow x_1^*$. This means that there is a strongly attractive period-four cycle traced for $t = 2001$ from the initial stock level $x_0$.

Figure 1b represents the optimal harvest $H^*$ associated with the optimal policy correspondence represented in Figure 1a. For example, the optimal harvest from the initial stock level $x_t = x_0$, $H^0 = f(x_0) - x_1^*$, can be obtained through the path $x_0 \rightarrow f \rightarrow g \rightarrow H^0$. We can observe in Figure 1b that there is no harvesting (moratoria) at low stock (normalized) levels $x \in [0, x']$, with $x' \simeq 0.56$, due to the fact that the optimal policy correspondence coincides with the growth function of the resource $x_{t+1}^* = f(x_t)$ for this range of stock values (see Figure 1a). With regard to the optimal policy dynamics represented in Figure 1a, this means that, a big harvesting $H^0$ from the initial stock level $x_t = x_0$ is followed by three periods of null harvest ($H^t = f(x_t^*) - x_{t+1}^* = 0; t = 1, 2, 3$) until the stock level $x_t = x_4^*$ is achieved. The current stock level $x_t = x_4^*$ represents the beginning of the period-four cycle in which the harvesting $H^4 = f(x_4^*) - x_1^* = 0.48$ million tonnes (see Figure 1b and Table 2, column IX, for $c^* = 0.2$) is followed by three periods of null harvest until $x_t = x_4^*$ is achieved again. We can observe in Figure 1a that the lowest stock of the cycle $x_{\min}^{CH} = x_1^* = 0.25$ is just the $B_{pa}$ for a discount factor $\delta = 0.9$.

Figure 1c represents the net revenue functions $R_t, t = 0, 1, 2, 3, 4$, which correspond to the current stock levels of the optimal policy dynamics $x_t = x_0, x_1^*, x_2^*, x_3^*, x_4^*$, as a function of the stock level in the next period $x_{t+1}$. For example, the net revenue $R^0$ associated with the initial stock level $x_t = x_0$ and the stock level in the next period $x_{t+1} = x_1^*$, is obtained through the path $x_0 \rightarrow a \rightarrow b \rightarrow R^0$. Notice that, in spite of the same optimal stock level in the next period $x_{t+1}^* = x_1^*$ obtained from $x_t = x_0, x_4^*$ (see Figure 1a), $R^0 > R^4$ (see Figure 1c) due to the fact that $H^0 > H^4$ (see Figure 1b). Finally, we can observe in Figure 1c that $R^t = 0, t = 1, 2, 3$, due to the null harvest associated with $x_t = x_1^*, x_2^*, x_3^*$ (see Figure 1b) which in turn implies the absence of AFC.

# 5 Concluding remarks

In this article we have analyzed a fishery with increasing marginal returns as well as fixed costs. Fixed costs are defined as avoidable fixed costs (AFC) in the sense that they are constant for a positive harvest level and zero when harvesting ceases. It has been demonstrated in the previous literature that in the presence of such non-concavities the optimal harvest policy may consist of cyclical behavior or pulse fishing instead of a steady state equilibrium.

In the present article we develop these models further by taking the stock effect during the harvesting season into account in a more general way than earlier. Further, we show that when the harvest function is stock dependent and there are increasing returns, steady state equilibria may very well be suboptimal and cyclical policies can be optimal regardless the size of the AFC even without re-entry costs. The previous literature has typically introduced re-entry costs in order to show that cyclical policies are optimal.

We have also shown that the role of the stock effect on costs and harvest within the harvest season. For example, if the harvest is more dependent on the stock in the beginning of the season, then extinction may be optimal even for stocks with high internal growth rate and without fixed cost if the discount rate is sufficiently high without being unreasonable. In the case of low discount rates the stock becomes in danger due to the cyclical behavior as this drives the stock below safe biological limits[1]. It is also shown that the risk of stock collapse increases significantly with increasing AFC as this implies higher period cycles. This is a fairly counterintuitive result as higher costs usually are thought of as having a conservative effect on the resource, and so are low discount rates. Furthermore, applying an oversimplified model that estimates costs by using the stock only in the beginning of the harvesting season will produce too high catch rates and thereby reinforce the tendency to overexploitation.

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**Table 1**

Numerical results without fixed costs for reasonable discount factor values $\delta \in [0.7, 0.95]$.

| $\delta$ | $x_{\min}^{SH}$ | Period of the cycle (SH) | $H^{SH}$ | $V(x_0)^{SH}$ | $x_{\min}^{CH}$ | Period of the cycle (CH) | $H^{CH}$ | $V(x_0)^{CH}$ |
|---|---|---|---|---|---|---|---|---|
| 0.7 | | extinction | 0.79 | 4.270 | 0.09 | 5 | 0.42 | 3.755 |
| 0.75 | 0.05 | 7 | 0.53 | 4.377 | 0.15 | 4 | 0.4 | 3.965 |
| 0.8 | 0.13 | 5 | 0.5 | 4.729 | 0.19 | 4 | 0.44 | 4.394 |
| 0.85 | 0.21 | 4 | 0.45 | 5.541 | 0.27 | 3 | 0.36 | 5.242 |
| 0.9 | 0.25 | 4 | 0.48 | 7.445 | 0.32 | 3 | 0.37 | 7.143 |
| 0.95 | 0.29 | 4 | 0.49 | 13.311 | 0.36 | 3 | 0.38 | 12.890 |

The value $x_{min}$ is the lowest stock of the cycle (million tonnes) in the optimal policy dynamics. The value H (million tonnes) is the optimal harvest in the cycle. $V(x_0)$ (thousand million NOK) is the net present value at initial condition $x_0$=0.68. SH and CH represent the standard and continuous harvesting case, respectively.

**Table 2**

Numerical results with avoidable fixed costs (AFC) for a discount factor δ=0.9.

| c* | AFC | $x_{\min}^{SH}$ | Period of the cycle (SH) | $H^{SH}$ | $V(x_0)^{SH}$ | $x_{\min}^{CH}$ | Period of the cycle (CH) | $H^{CH}$ | $V(x_0)^{CH}$ |
|---|---|---|---|---|---|---|---|---|---|
| 0.1 | 0.109 | 0.2 | 5 | 0.57 | 7.131 | 0.25 | 4 | 0.48 | 6.783 |
| 0.2 | 0.218 | 0.2 | 5 | 0.57 | 6.864 | 0.25 | 4 | 0.48 | 6.466 |
| 0.3 | 0.327 | 0.2 | 5 | 0.57 | 6.598 | 0.2 | 5 | 0.57 | 6.162 |
| 0.4 | 0.437 | 0.16 | 6 | 0.65 | 6.341 | 0.2 | 5 | 0.57 | 5.896 |
| 0.45 | 0.491 | 0.16 | 6 | 0.65 | 6.224 | 0.2 | 5 | 0.57 | 5.763 |
| 0.5 | 0.546 | 0.16 | 6 | 0.65 | 6.108 | 0.2 | 5 | 0.57 | 5.629 |

Avoidable fixed costs (thousand million NOK) are given by AFC=c*v, where c* is a percentage of the variable cost per vessel c=0.0010917 (thousand million NOK), and v=1000 is the fleet size. The value $x_{min}$ is the lowest stock of the cycle (million tonnes) in the optimal policy dynamics. The value H (million tonnes) is the optimal harvest in the cycle. $V(x_0)$ (thousand million NOK) is the net present value at initial condition $x_0$=0.68. SH and CH represent the standard and continuous harvesting case, respectively.

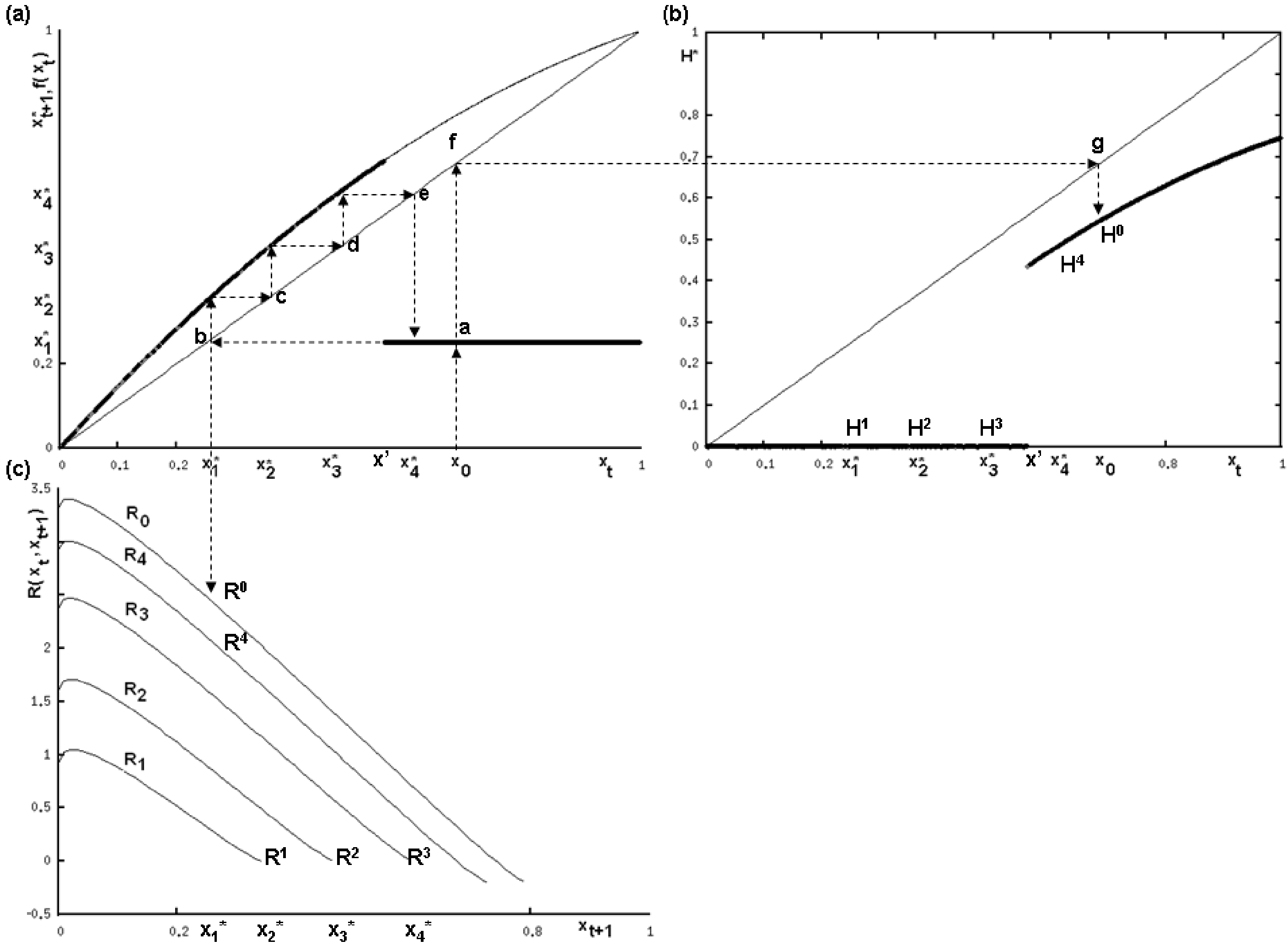


Figure 1. (a) Growth function of the resource f(x), optimal policy correspondence, and optimal policy dynamics. (b) Optimal harvest H*. (c) Net revenue functions.